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SIMPLIFIED THEORETICAL METHODS OF PREDICTING THE MOTIONS OF A CATAMARAN IN WAVES

by

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NOTATION

A_W	Area of waterplane of one hull
B	Breadth of one hull
B_c	Transverse distance from longitudinal axis of symmetry of catamaran to longitudinal axis of one hull
B_m	Overall breadth of catamaran
$\overline{BG}$	Vertical distance of center of gravity above center of buoyancy
b	Coefficient of the restoring moment
CG	Center of gravity
$\overline{F}$	Exciting moment
g	Gravitational acceleration
$\overline{GM}$	Transverse metacentric height
I_o	Moment of inertia of waterplane area of both hulls with respect to to the longitudinal axis of symmetry of the catamaran
I_T	Moment of inertia of waterplane area of one hull with respect to its longitudinal axis
k_ϕ	Transverse gyradius
L	Hull length between perpendiculars
m	Mass moment of inertia
n	Damping coefficient
t	Time
V	Speed of advance
z_A	Heave amplitude
ε	Phase angle
ζ_A	Wave amplitude
ζ_W	Wave height
θ_A	Pitch amplitude
κ	Wave number = $2\pi/\lambda$
λ	Wavelength
ρ	Water density
ϕ_A	Roll amplitude
ω	Circular frequency

∇_1 Volume of water displaced by one hull

∇_2 Volume of water displaced by both catamaran hulls

ABSTRACT

Simplified methods are discussed for estimating (1) the pitch and heave of catamarans in head seas based on theory which has proven successful for conventional single hulled ships, and (2) the roll of catamarans in beam seas by representing the small amount of roll as alternate heaving of the two hulls. Both prediction methods neglect interaction effects between the two hulls. Computed values of pitch, heave, and roll are compared with experimental data from model tests of a catamaran in regular waves. Documentation of the computer program for predicting the roll of a catamaran in regular and irregular seas is presented in the appendices.

ADMINISTRATIVE INFORMATION

This work was performed at Naval Ship Research and Development Center (NSRDC) primarily under the Naval Ship Systems Command (NAVSHIPS) Exploratory Development Applied Hydromechanics Program, Subproject SF 35. 421.006, Task 1713. Development of the computer routine for predicting roll in beam seas was undertaken as part of a conceptual research feasibility study of catamaran aircraft carriers and funded from NSRDC in-house Project 1-H71-001, Task ZF 35.412.002.

INTRODUCTION

The growing interest in catamarans makes it desirable to be able to predict the motions of these ships by techniques similar to those which have been developed for monohulls. Existing computer programs for predicting the pitch and heave motions of single-hulled ships provide a first approach for predicting the pitch and heave of catamarans in head seas. The basic assumption in the present approach is that the hulls are widely separated, i.e., interaction effects between the two hulls are neglected. With this assumption, it is relatively simple to write a computer program for estimating the roll motion of a catamaran in beam seas. Since rolling of a catamaran takes place with small angles, it can be regarded as alternate heaving of the two hulls. Therefore, parts of the program to compute pitch and heave can be used for the prediction of roll of a catamaran. In this report the motions estimated in the manner described above are compared with experimentally obtained data from catamaran Model 5061 which has been tested at this Center with various hull separations.

Since the hulls of a catamaran generally have proportions different from those of a conventional ship hull, the effect of the beam-draft ratio on the motions in head waves is also examined to some extent.

MOTION PREDICTION METHODS

PITCH AND HEAVE

The pitch and heave motions of conventional ships in head waves at Froude numbers up to 0.45 have been predicted quite successfully using the Frank Close-Fit Ship-Motion Computer Program YF17.[1] The regular wave responses are computed according to an improved version of the Korvin-Kroukovsky strip theory. An essential part of the program is the computation of the sectional added mass and damping coefficients by either the Lewis-form method or the more accurate but time-consuming close-fit method. The same program (hereafter referred to as YF17) has been used for the calculation of catamaran pitch and heave in head seas presented in this report. The catamaran considered here, Model 5061, has hulls with asymmetric sections forward of midship; see Figure 1. However, YF17 considers only a single body which is symmetrical about a vertical longitudinal plane. Therefore, in the equations of motion the added mass and the damping coefficient computed for each section were those for a Lewis section having the same waterline width, draft, and sectional area as one hull of the catamaran. These sections are shown in Figure 2. This Lewis-form method has been used in lieu of the close-fit method for many conventional ships (except those with large bulbous bows) without significantly effecting the resultant computed motions. Experience gained with computation procedures which differ only slightly from those used in YF17, in combination with Lewis sections, indicates that the agreement between experiment and theory is better for beamy hulls than for rather narrow hulls; see Joosen et al.[2] and Vassilopoulos and Mandel.[3] Catamaran hulls generally belong to the latter category; those considered in this report

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[1] References are listed on page 35.

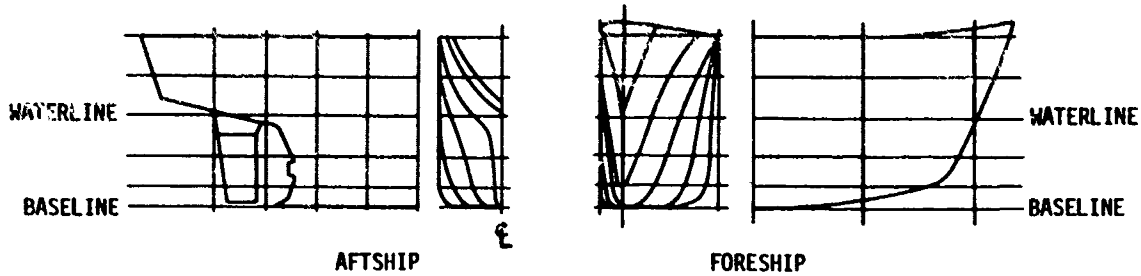


Figure 1 - Hull Lines of Catamaran Model 5061

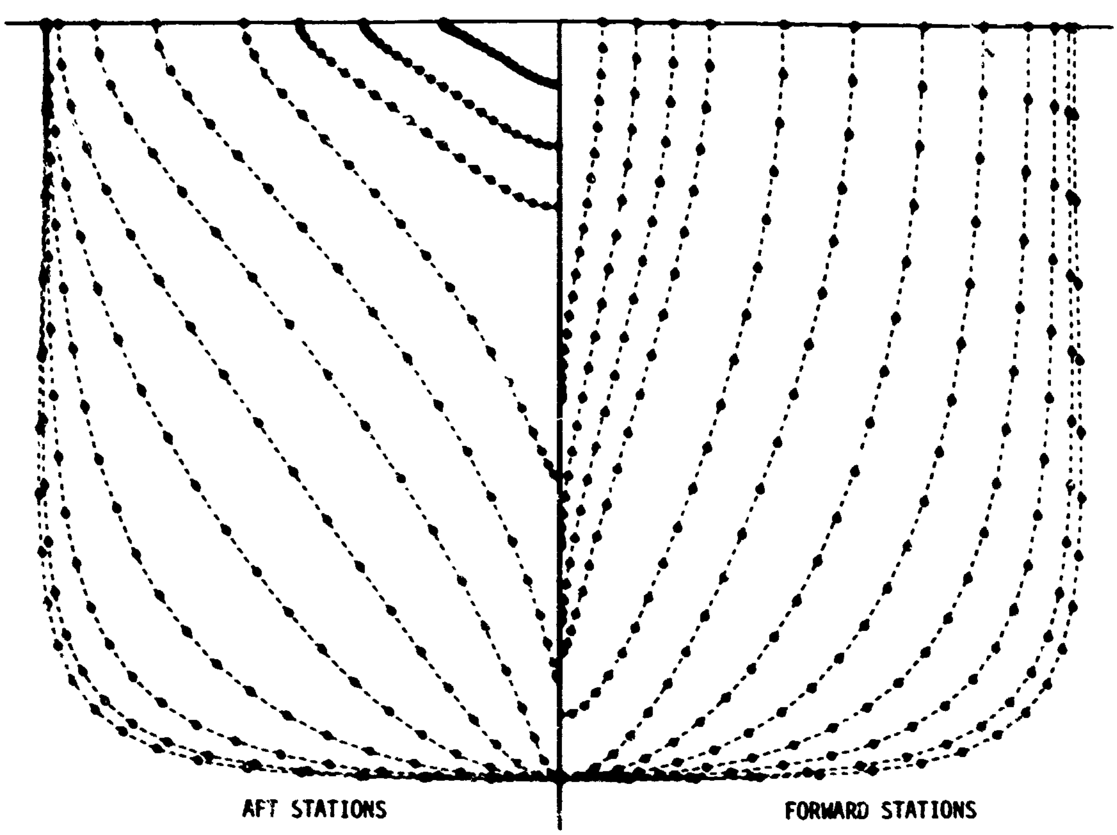


Figure 2 - Lewis Sections with the Same Waterline Width, Draft, and Sectional Area as One Hull of the Catamaran

have a beam-draft ratio of 1.3. To investigate the effect of the beam-draft ratio, the computed motions in head waves of the catamaran with the narrow hulls are compared with the computed motions of a ship that has the same length, draft, and displacement as the catamaran, and waterline widths and sectional areas equal to those of both catamaran hulls. The sections of the conventional ship are given in Figure 3. Because of the limitations of the prediction method for catamarans, the compared motions of the two ships cannot be regarded as correct in the quantitative sense, but only qualitatively.

ROLL

A slight modification of the theory outlined by Wahab[4] was used to develop a computer program for predicting the rolling characteristics of a catamaran in both regular and irregular seas. Complete documentation for this program, designated RLAC, is presented in Appendixes A-D.

The theory is based on the assumption that the rolling of a catamaran can be represented by alternate heaving of the two hulls without significant error since the roll angles as well as the roll damping and added moments of inertia of each hull are small.

In determining the exciting moment in beam waves, it was assumed that the presence of the ship did not change the pressure distribution in the undisturbed wave. The exciting moment was obtained from the hydrostatic pressure acting on the ship with a correction for the Smith effect. This approach is known to give reasonable results in head waves, but no verification has been made for the case of beam waves.

The uncoupled linear equation of motion is

$$m \ddot{\phi} + n\dot{\phi} + b\phi = \bar{F} \sin \omega t \tag{1}$$

After the starting transient has died out, the solution of this equation is

$$\phi = \phi_A \sin (\omega t + \varepsilon) \tag{2}$$

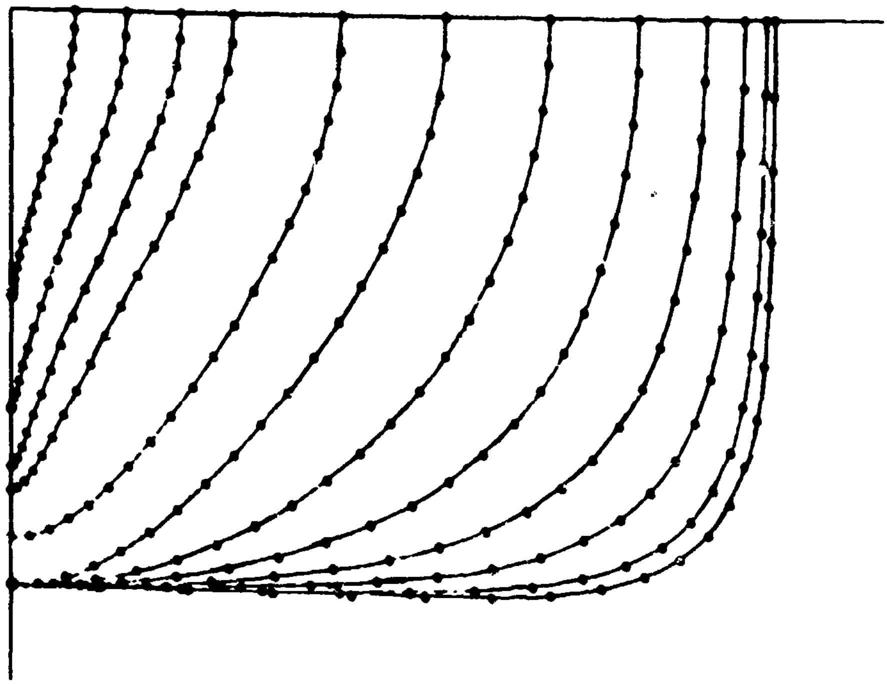


Figure 3a - Foreship

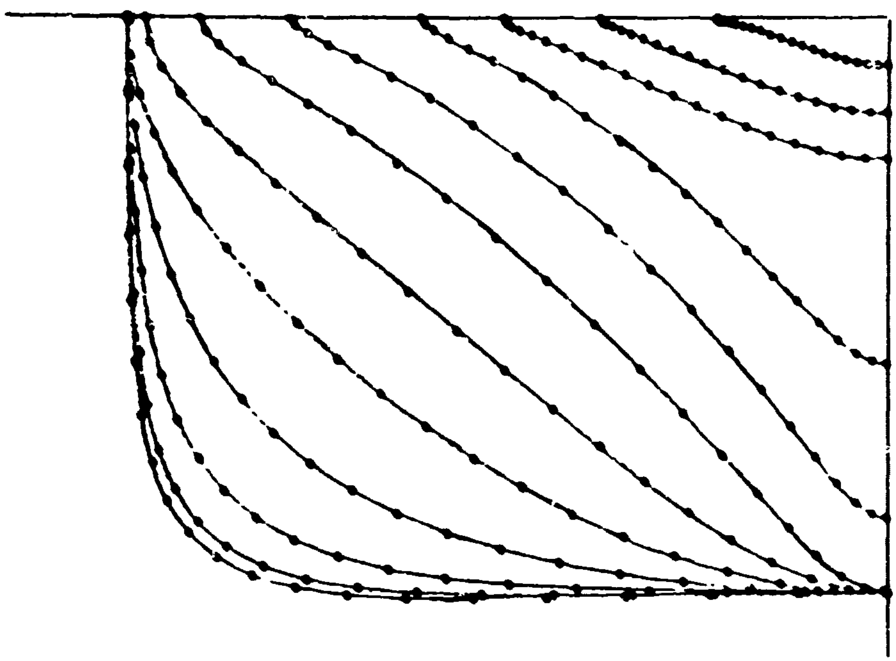


Figure 3b - Aftship

Figure 3 - Lewis Sections with the Same Waterline Width, Draft, and Sectional Area as Both Catamaran Hulls

$$\phi_A = \bar{F} \Big/ \sqrt{(b - m\,\omega^2)^2 + n^2\,\omega^2} \tag{3}$$

$$\varepsilon = \text{atan}\,\frac{\omega\, n}{m\,\omega^2 - b} \tag{4}$$

For regular beam waves the exciting moment $\bar{F}$ is

$$\bar{F} = \zeta_W \rho g \sqrt{\left[B_c A_W e^{(-\kappa\, \nabla_1/A_W)} \sin\,(\kappa\, B_c)\right]^2 + \left[\kappa\,(I_T - \overline{BG}\,\nabla_1)\,\cos\,(\kappa\, B_c)\right]^2} \tag{5}$$

where $\kappa = 2\pi/\lambda$.

The coefficient b of the restoring moment may be calculated by

$$b = \overline{GM}\,\rho g\,\nabla_2 = (I_o/\nabla_2 - \overline{BG})\,\rho g\,\nabla_2 \tag{6}$$

When the catamaran rolls with amplitude ϕ_A, each hull heaves with amplitude $\phi_A B_c$ in addition to the rolling. Therefore, the mass moment of inertia is subdivided as follows:

$$m = m_c + m_{\phi\phi} + B_c^2 m_{zz} \tag{7}$$

where m_c is the transverse moment of inertia of the catamaran itself,

$m_{\phi\phi}$ is the added moment of inertia due to rolling of both hulls, and

m_{zz} is the added mass due to the heaving motion of both hulls.

Since $m_{\phi\phi}$ is small compared to $B_c^2\, m_{zz}$, it is neglected.

The damping coefficient can be subdivided as follows:

$$n = B_c^2 n_{zz} + n_{\phi\phi} \tag{8}$$

where $n_{\phi\phi}$ is the damping coefficient due to rolling motion of both hulls and n_{zz} is the damping coefficient due to heaving motion of both hulls. Since $n_{\phi\phi}$ is small compared to $B_c^2 n_{zz}$, it is also neglected.

Program RLAC incorporates Subroutines ADMAB and NILS from Program YF17 for computing the added mass and damping coefficient due to heave. As

with pitch and heave, the Lewis-form sections shown in Figure 2 are used for the roll computation of the catamaran being studied, and interaction effects between the two hulls are neglected.

In view of the aforementioned limitations of the existing theory of catamaran roll, refinements such as (1) correction for forward speed effects on the coefficients of the equations of motion and (2) correction to the exciting moment for added mass and damping forces associated with the oribital motion of the water particles in the waves have not been made.

Program RLAC can also be used to predict catamaran roll in irregular seas. Roll is computed for a range of wave frequencies using an arbitrary wave steepness (ζ_w/λ) of 1/50. The method of linear superposition on the sea spectrum given by the Pierson-Moskowitz formulation is used for prediction of the roll displacement and acceleration at various sea states. Calculations for catamaran Model 5061 at significant wave heights of 4, 10, 20, and 30 ft are contained in the sample output shown in Appendix C.

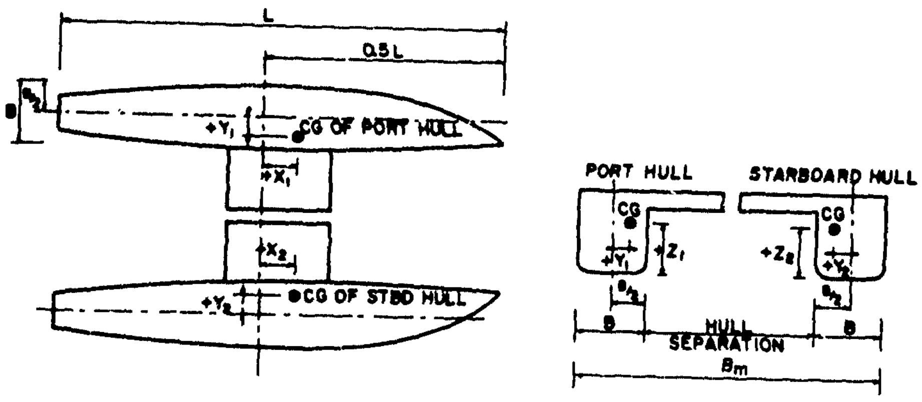
COMPARISON OF COMPUTED AND MEASURED DATA

The particulars of catamaran Model 5061 and the dynamic conditions for which it was tested are given in Figures 4 and 5, respectively. In Figures 6 and 7 the computed heave and pitch motions are compared with results of experiments in head waves. The dashed curves in the figures represent the computed motions of a ship with the same length, draft, and displacement as the catamaran and with waterline widths and sectional areas equal to those of both of the catamaran hulls. A comparison between computed and measured roll motions for the catamaran is made in Figure 8.

HEAVE

Theory versus Experiment for the Catamaran

For zero speed and all hull separations, it is seen in Figure 6 that the computed values agreed well with measured heave except for $\lambda/L \approx 1.1$ where a slight peak was obtained. Trends were maintained for the remaining speeds. However, measured amplitudes, especially in the resonance region, were significantly lower than predicted for $\lambda > L$ but



L = 12.43 Ft

B = 17.00 in

Draft = 12.78 in

Weight of each hull = 631 lb

Longitudinal Gyradius = 0.25 L

INCHES	HULL SEPARATION IN INCHES 12	18	24	30	36
X_1	1.4	1.4	1.4	1.4	1.4
X_2	-2.1	-2.1	-2.1	-2.1	-2.1
Y_1	0.7	1.1	1.5	1.9	2.2
Y_2	0.3	0.6	0.9	1.2	1.4
Z_1	13.4	13.4	13.4	13.4	13.4
Z_2	13.2	13.2	13.2	13.2	13.2

Figure 4 - Particulars of Catamaran Model 5061

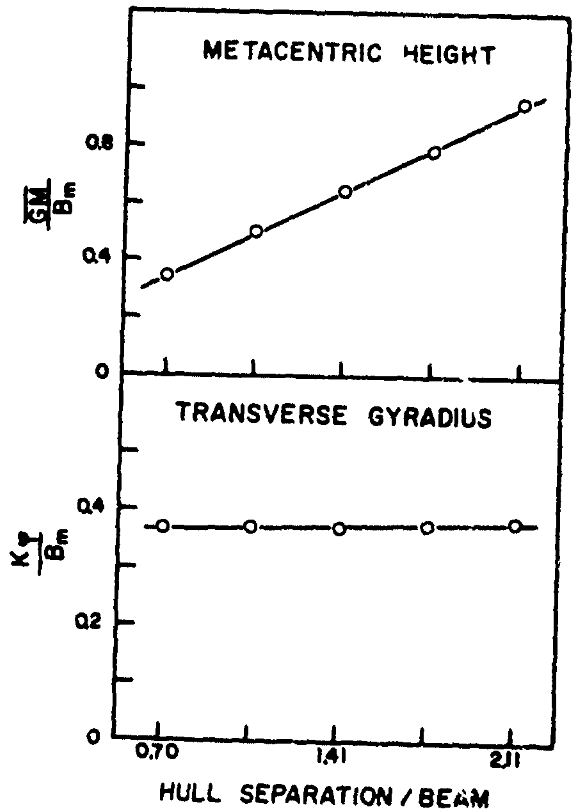


Figure 5 - Metacentric Height and Transverse Gyradius of Model 5061

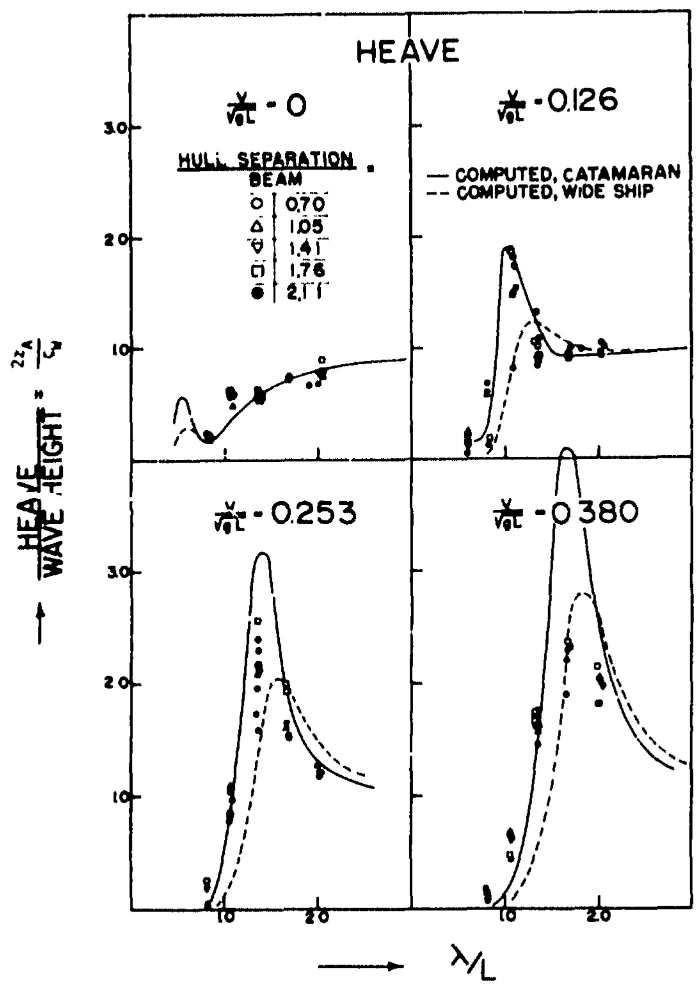


Figure 6 - Heave Transfer for Head Waves and Various Speeds

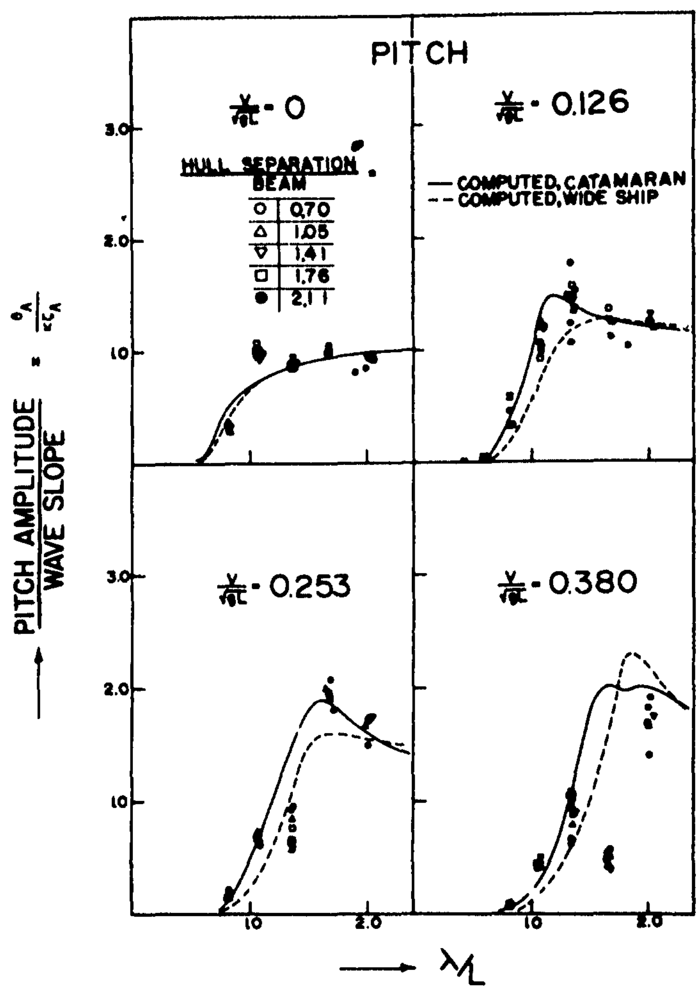


Figure 7 - Pitch Transfer for Head Waves and Various Speeds

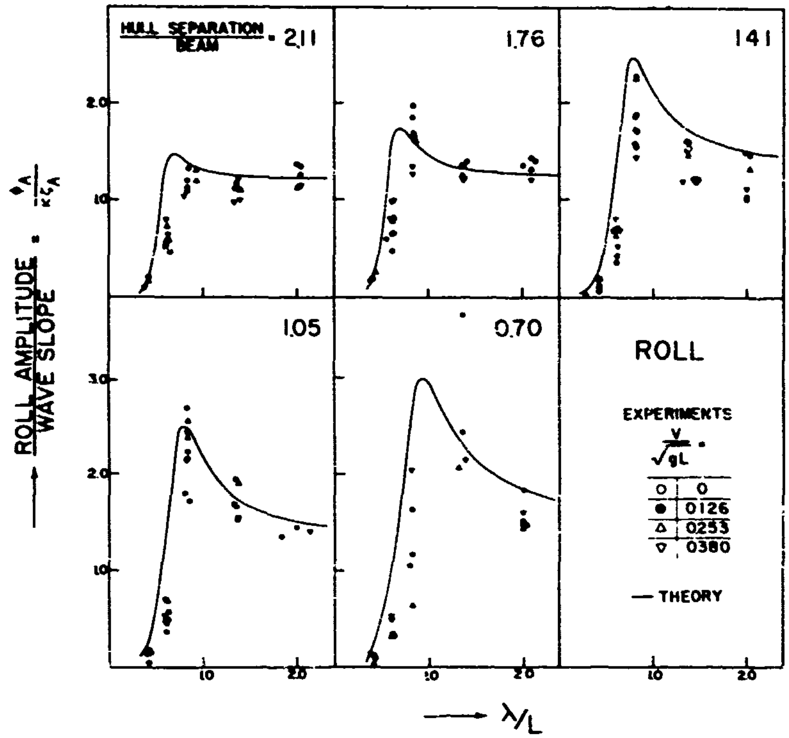


Figure 8 - Roll Transfer in Beam Waves for Various Hull Separations

was slightly larger than predicted for $\lambda < L$ in most cases. It has been shown[2,3] that the present state-of-the-art calculation procedure yields poor results even for conventional ships with low beam-draft ratios. It overestimates the pitch and heave response amplitudes, particularly at resonance. Vassilopoulos and Mandel[3] attribute this to the use of Lewis sections. The discrepancies found in the present comparison may possibly also be partly attributed to imperfections in the theory as applied to catamarans.

Catamaran versus Conventional Ship

The curves in Figure 6 indicate that a catamaran may be expected to heave more than a monohull ship with the same length, draft, and displacement. However, since the theory overestimates the motions for low beam-draft ratio hulls, the difference will actually be smaller than the two computed curves indicate.

PITCH

Theory versus Experiments for the Catamaran

For the two lowest investigated speeds, the experimentally obtained pitch shown in Figure 7 had about the same trend as the predictions. For the two higher speeds, however, there was a distinct difference in the character of the measured and computed transfer curves; this indicates that the interaction effects between the hulls are most likely not negligible. To some extent, the difference may also be due to imperfections in the computation procedure as discussed in the previous section.

Catamaran versus Conventional Ship

The pitch motion of a catamaran may be expected to be large compared to that of a ship with the same length, draft, and displacement, because of the smaller beam-draft ratio of the catamaran hulls.

ROLL

The general nature of the roll behavior in Figure 8, i.e., slope and location of maxima, agreed fairly well with prediction. It is noted that the computation is primarily valid for zero speed since no

speed-dependent terms were included in the equation of motion. However, on the basis of the experimental data, some functional dependence of roll damping on hull separation, and to a lesser extent on forward speed, is apparent. Therefore, it may be worthwhile to refine the equation of motion but maintain the assumption of no mutual influence between the hulls.

CONCLUDING REMARKS

It appears that neglecting the interaction effects between the hulls does not prevent reasonable results when computing roll in beam seas. Better results may possibly be obtained by including speed-dependent terms in the equation of motion. The pitch and heave motions in head waves could not be satisfactorily predicted at the high Froude numbers of 0.25 and 0.38. The discrepancy may be partly attributed to the unsatisfactory performance of the calculation procedure for low beam-draft ratio hulls.

The computations also showed that because of the small beam-draft ratio of its hulls, the behavior of a catamaran in head waves may be significantly worse than the behavior of a ship with the same length, draft, and displacement.

APPENDIX A

PROCEDURE AND NOTATION USED IN COMPUTER PROGRAM RLAC

BASIC HULL GEOMETRY

*	BPL	$= L_{BP}$	= length between perpendiculars of each hull (ft)	
*	NOS	$= n_s$	= number of stations	
*	ST(K)	$= Sta_k$	= station number (Sta 0 must be at the FP) (Sta 20 must be at the AP)	$(k=1,n_s)$
*	NM(K)	$= m_k$	= number of waterlines at which offsets are given	$(k=1,n_s)$
	X(K)	$= x_k$	= distance of Sta_k aft of FP (ft) = $Sta_k \cdot L_{BP}/20$	$(k=1,n_s)$

If $m_k = 0$

*	B(K)	$= b_k$	= full beam of one hull, at the waterline (ft)	$(k=1,n_s)$
*	H(K)	$= h_k$	= distance from keel to waterline (ft)	$(k=1,n_s)$
*	CA(K)	$= C_{A_k}$	= area coefficient	$(k=1,n_s)$
	AR(K)	$= A_k$	= sectional area (ft^2) = $C_{A_k} \cdot b_k \cdot h_k$	$(k=1,n_s)$

If $m_k > 0$

*	Z(J,K)	$= z_{j,k}$	= distance above the baseline (ft) ($z_{1,k}$ must be at the keel) ($z_{m_k,k}$ must be at the waterline	$(j=1,m_k)$ $(k=1,n_s)$
*	Y(J,K)	$= y_{j,k}$	= half beam of one hull, at $z_{j,k}$ (ft)	$(j=1,m_k)$ $(k=1,n_s)$
	B(K)	$= b_k$	$= 2 \cdot y_{m_k,k}$	$(k=1,n_s)$
	H(K)	$= h_k$	$= z_{m_k,k} - z_{1,k}$	$(k=1,n_s)$
	AR(K)	$= A_k$	$= 2 \int y \, dz$ (numerical intergration by the Simpson rule)	$(k=1,n_s)$
	CA(K)	$= C_{A_k}$	$= A_k/(b_k \cdot h_k)$	$(k=1,n_s)$

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*Input values.

Note: The FORTRAN designation for the variables is given in the first column, and the normal notation in the second column.

AM(K)	= $A_k \cdot x_k$	=	moment of the area of Sta_k about the FP ($k=1,n_s$)
MS	= $\otimes$	=	value of k where $Sta_k = 10$
BM	= B	=	full beam of one hull at amidships (ft) = $b_{\otimes}$
HM	= H	=	draft (keel to WL) at amidships (ft) = $h_{\otimes}$
RHO	= ρ	=	water density = 1.9905 $lb\text{-}sec^2/ft^4$
G	= g	=	acceleration of gravity = 32.174 ft/sec^2
VOL1	= ∇_1	=	volume of water displaced by one hull (ft^3) = $\int_0^L A\, dx$
VOL	= ∇_2	=	volume displaced by both hulls (ft^3) = $2 \cdot \nabla_1$
TM	= M	=	total mass of the catamaran ($lb\text{-}sec^2/ft$) = $\rho \nabla_2$
DLBS	= Δ	=	displacement of catamaran (lb) = $\rho\, g\, \nabla_2$
DTONS	=	=	displacement of catamaran (tons) = $\Delta/2240$
AW	= A_W	=	area of waterplane of one hull (ft^2) = $\int_0^L b\, dx$
OIP	= I_T	=	moment of inertia of waterplane area of one hull with respect to the longitudinal axis of the hull = $2/3 \int_0^L b^3\, dx$
CB	= C_B	=	block coefficient of one hull = $\nabla_1/(L_{BP} \cdot B \cdot H)$
CW	= C_W	=	waterplane coefficient of one hull = $A_W/(L_{BP} \cdot B)$
BOY	= LCB	=	distance of center of buoyancy aft of FP (ft) = $\left[\int_0^L A\, x\, dx\right] \Big/ \left[\int_0^L A\, dx\right]$
CBL	= LCB/L_{BP}		
FLC	= LCF	=	distance of center of floatation aft of FP (ft) = $LCB + \left[\int_0^L (x - LCB)\, b\, dx\right] \Big/ [A_W] = \left[\int_0^L b\, x\, dx\right] \Big/ [A_W]$
CFL	= LCF/L_{BP}		
BL	= L/B	=	L_{BP}/B
BT	= B/H		

OTHER SHIP PARAMETERS

*	BP	=	L	=	length between perpendiculars of each hull (ft) Note: If this length differs from the one used for the basic hull geometry calculations, all the basic parameters (∇, B, H, etc.) are scaled by the appropriate linear ratio.
			CL	=	centerline
			CG	=	center of gravity
			CB	=	center of buoyancy
*	DK	=	$\overline{KD}$	=	vertical distance of deck above keel (ft)
*	GK	=	$\overline{KG}$	=	vertical distance of CG above keel (ft)
*	BK	=	$\overline{KB}$	=	vertical distance of CB above keel (ft)
	GD	=	$\overline{GD}$	=	distance of deck above CG (ft) = $\overline{KD} - \overline{KG}$
	BG	=	$\overline{BG}$	=	distance of CG above CB (ft) = $\overline{KG} - \overline{KB}$
	GM	=	$\overline{GM}$	=	metacentric height (ft) = $\overline{KB} + \overline{BM} - \overline{KG} = I_o/\nabla_2 - \overline{BG}$
*	YL	=	B_c	=	transverse distance from CL of catamaran to CL of one hull (ft)
*	YLP	=	B_d	=	transverse distance from CL of catamaran to outer edge of the deck (ft)
*	RG	=	k_ϕ	=	transverse gyradius (ft)
	OI	=	I_o	=	moment of inertia of the waterplane area of both hulls with respect to the longitudinal axis of symmetry of the catamaran = $2\ (I_T + B_c^{\ 2} A_w)$
	CRM	=	b	=	coefficient of the restoring moment = $\overline{GM}\ \Delta$
			m_c	=	transverse moment of inertia of the catamaran = $k_\phi^{\ 2}\ \rho\ \nabla_2$

ROLLING MOTIONS IN REGULAR WAVES

H21	=	ζ_W/λ	=	wave height to length ratio = 1/50
WS	=	$\kappa\zeta_A$	=	wave slope = $\pi/50$

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*Input values.

*	OMIN	=	$\left(\omega\sqrt{\frac{L}{g}}\right)_1$	= minimum nondimensional wave frequency, generally 0.2
*	OMAX	=	$\left(\omega\sqrt{\frac{L}{g}}\right)_{n_F}$	= maximum nondimensional wave frequency, generally 10.0
*	DOM	=	$\Delta\left(\omega\sqrt{\frac{L}{g}}\right)$	= increment of nondimensional frequency, generally 0.2
	NFR	=	n_F	= number of frequencies = [(OMAX-OMIN)/DOM] + 1

Calculated for each of the n_F frequencies:

	OMLG(N)	=	$\left(\omega\sqrt{\frac{L}{g}}\right)_n$	= $\left(\omega\sqrt{\frac{L}{g}}\right)_{n-1} + \Delta\left(\omega\sqrt{\frac{L}{g}}\right)$
	OM(N)	=	ω	= wave frequency (rad/sec) = $\left(\omega\sqrt{\frac{L}{g}}\right) \Big/ \sqrt{\frac{L}{g}}$
	WL	=	λ	= wavelength (ft) = $2\pi g/\omega^2$
	WLL	=	λ/L	= ratio of wavelength to ship length
	WH2	=	ζ_W	= wave height (ft) = $\lambda/50$
	WH	=	ζ_A	= wave amplitude (ft)
**	A33(N)	=	a_{33}	= added mass due to heave of each hull/$(\rho\nabla_1)$
**	B33(N)	=	b_{33}	= damping coefficient for each hull /$(\rho\nabla_1 \sqrt{g/L})$
			m_{zz}	= added mass due to heave of both hulls = $a_{33}\ \rho\nabla_2$
			n_{zz}	= damping coefficient due to heave of both hulls = $b_{33}\ \rho\nabla_2\ \sqrt{g/L}$

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*Input values.

**Values of a_{33} and b_{33} may be input or calculated in the program. If calculated by this program, the sections are represented by the Lewis-form method, and the two-dimensional added mass and damping coefficients are calculated according to the Grim method by Subroutine ADMAB, which is abstracted from Program YF17, but was initially written by Stevens Institute of Technology. If a_{33} and b_{33} are input directly, they may be obtained from Program YF17 which uses either the Lewis-form or the close-fit method for each section independently, as desired. In either case, the three-dimensional values are computed according to strip theory by using Subroutine NILS (also abstracted from YF17) for computation of the Simpson weight coefficients.

CM = m = mass moment of inertia = $m_c + B_c^2\, m_{zz}$

CN = n = damping coefficient = $B_c^2\, n_{zz}$

PWL = κ = wave number = $2\pi/\lambda$

ANG = $\kappa\, B_c$ = $2\pi B_c/\lambda$

FBAR = $\bar{F}$ = exciting moment

$$= \zeta_W \rho g \sqrt{\left[B_c A_W e^{(-\kappa \nabla_1/A_W} \sin (\kappa B_c)\right]^2 + \left[\kappa(I_T - \overline{BG}\, \nabla_1) \cos (\kappa\, B_c)\right]^2}$$

PHIB = ϕ_A = roll amplitude (rad) = $\bar{F} / \sqrt{(b - m\omega^2)^2 + n^2\, \omega^2}$

PHI = $\dfrac{\phi_A}{\kappa\, \zeta_A}$ = roll amplitude / wave slope

RAOR = $\left(\dfrac{\phi_A}{\zeta_A}\right)^2$ = response amplitude operator for roll displacement $(\text{rad/ft})^2$

RAOA = $\left(\dfrac{\phi_A\, \omega^2}{\zeta_A}\right)^2$ = response amplitude operator for roll acceleration $(\text{rad/ft/sec}^2)^2$

ROLLING MOTIONS IN IRREGULAR WAVES

* NSWH = n_H = number of significant wave heights for irregular sea computations

* H13(M) = $H_{1/3_m}$ = significant wave height = average of the highest one-third wave heights $\}$ $(m=1, n_H)$

Calculated for each $H_{1/3}$, ω combination:

SW(N) = $s(\omega)$ = Pierson-Moskowitz sea spectral formulation $(\text{ft}^2\ \text{sec})$

$= (A/\omega^5)\ e^{-B/\omega^4}$, where $A = 0.0081\ g^2$ and $B = 33.56/(H_{1/3})^2$

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*Input values.

FROLL(N,M) = $(\phi_A/\zeta_A)^2\ s(\omega)\ (\mathrm{rad}^2\ \mathrm{sec})$

FACC(N,M) = $(\phi_A\omega^2/\zeta_A)^2\ s(\omega)\ (\mathrm{rad}^2/\mathrm{sec}^3)$

Calculated for each $H_{1/3}$:

$E_1 = 2\int(\phi_A/\zeta_A)^2\ s(\omega)\ d\omega\ (\mathrm{rad}^2)$

$\phi_{1/3}$ = amplitude of significant roll angle (rad) = $1.41\sqrt{E_1}$

RDEG(M) = $\phi_{1/3}'$ = amplitude of significant roll angle (deg) = $\phi_{1/3} \cdot (180/\pi)$

$E_2 = 2\int(\phi_A\omega^2/\zeta_A)^2\ s(\omega)\ d_\omega\ (\mathrm{rad}^2/\mathrm{sec}^4)$

$a_{1/3}$ = amplitude of significant roll acceleration $(\mathrm{rad}/\mathrm{sec}^2) = 1.41\sqrt{E_2}$

ADEG(M) = $a_{1/3}'$ = amplitude of significant roll acceleration $(\mathrm{deg}/\mathrm{sec}^2) = a_{1/3}\ (180/\pi)$

AVG(M) = $a_{v_{1/3}}$ = (amplitude of significant vertical roll acceleration at outer edge of deck)/(gravitational acceleration) = $a_{1/3}\ B_d/g$

AHG(M) = $a_{h_{1/3}}$ = (amplitude of significant horizontal roll acceleration on the deck)/(gravitational acceleration) = $a_{1/3}\ \overline{GD}/g$

APPENDIX B

FORMAT OF INPUT FOR PROGRAM RLAC

CARD SET 1 (one card)

COLUMNS	FORMAT	FORTRAN	Explanation
2-72	12A6	TITLE	Any identification to be printed at the top of each page of the output

CARD SET 2 (one card)

COLUMNS	FORMAT	FORTRAN	Explanation
1- 9	F9.3	BPL	L = length between perpendiculars of each hull (ft)
10-18	F9.3	OMIN	Minimum nondimensional wave frequency: $\omega\sqrt{\frac{L}{g}}$
19-27	F9.3	OMAX	Maximum nondimensional wave frequency: $\omega\sqrt{\frac{L}{g}}$
28-36	F9.3	DOM	Increment of nondimensional wave frequency: $\omega\sqrt{\frac{L}{g}}$
37-45	F9.3	CST	Linear ratio for converting input dimensions on Card Sets 3 and 4 to the size ship specified in Columns 1-9 of this card
46-54	I9	NOS	n_s = number of stations = number of cards in Set 3
55-63	I9	IAMD	Control for added mass (a) and damping coefficient (b) If IAMD=0, a and b will be calculated by this program by using the Lewis-form method for the sections. If IAMD=1, values of a and b are input in Set 5.

CARD SET 3 (one card for each station)

COLUMNS	FORMAT	FORTRAN	Explanation
1- 9	F9.4	ST(K)	Sta_k = station number
10-18	F9.4	B(K)	b_k = full beam at the waterline (omit if $m_k > 0$)
19-27	F9.4	H(K)	h_k = distance from keel to waterline (omit if $m_k > 0$)
28-36	F9.4	CA(K)	C_{A_k} = area coefficient = $\frac{\text{area}}{b_k \cdot h_k}$ (omit if $m_k > 0$)
37-45	I9	NM(K)	m_k = number of waterlines for which offsets are given in Card Set 4 If values of b_k, h_k, and C_{A_k} are given, then m_k=0.

$k = 1, n_s$

Note: Cards in Set 3 must be in order of ascending station numbers. Stations 0 (at FP), 10 (at amidships), and 20 (at AP) must be included, together with enough additional stations to define the sectional area curve. The maximum number of stations is 30.

CARD SET 4 (one subset for each station with $m_k > 0$)

COLUMNS	FORMAT	FORTRAN	Explanation
1-72*	8F9.4	Y(J,K)	$y_{j,k}$ $(j=1,m_k)$ = half beam at $z_{j,k}$
1-72*	8F9.4	Z(J,K)	$z_{j,k}$ $(j=1,m_k)$ = distance above the baseline

Note: Values of z must be in ascending order, with $z_{1,k}$ at the keel and $z_{m_k,k}$ at the waterline.

Subsets must be in order of ascending station numbers.
If $m_k = 0$, there will be no cards in the subset.

If $m_k > 0$, there will be 2, 4, or 6 cards in the subset.

CARD SET 5

COLUMNS	FORMAT	FORTRAN	Explanation
1-72*	8F9.4	A33(N)	a_n $(n=1,n_F)$ = added mass / $(\rho\nabla)$
1-72*	8F9.4	B33(N)	b_n $(n=1,n_F)$ = damping coefficient / $\left(\rho\nabla \sqrt{\frac{g}{L}}\right)$

Note: n_F = number of wave frequencies = ((OMAX-OMIN)/DOM) + 1

If IAMD=0, there will be no cards in this set.
If IAMD=1, the values of a_n and b_n can be obtained from the columns labeled A33 and B33, respectively, of the output from Program YF17 which uses either the Lewis-form or the close-fit method as desired.

CARD SET 6 (one card)

COLUMNS	FORMAT	FORTRAN	Explanation
1-2	I2	NSWH	n_H = number of significant wave heights for irregular sea computations ≤ 4

CARD SET 7 (one card)

COLUMNS	FORMAT	FORTRAN	Explanation
1-36	4F9.4	H13(M)	$H_{1/3_m}$ $(m=1,n_H)$ = significant wave height (ft)

CARD SET 8 (one card)

COLUMNS	FORMAT	FORTRAN	Explanation
1-2	I2	NC	n_c = number of conditions = number of cards in Set 9

*Continue on additional cards if necessary.

CARD SET 9 (one card for each condition)

COLUMNS	FORMAT	FORTRAN	Explanation	
1- 9	F9.4	BP	L = length between perpendiculars (ft)	
10-18	F9.4	DK	KD = distance of deck above keel (ft)	at LCB
19-27	F9.4	GK	KG = distance of CG above keel (ft)	at LCB
28-36	F9.4	BK	KB = distance of CB above keel (ft)	at LCB
37-45	F9.4	YLP	B_d = transverse distance from CL of catamaran to outer edge of deck (ft)	
46-54	F9.4	YL	B_c = transverse distance from CL of catamaran to CL of one hull (ft)	
55-63	F9.4	RG	k_ϕ = transverse gyradius (ft)	

Note: The irregular sea computations are done for the ship length specified on this card. This L can differ from the value on Card 1 which is used only for nondimensional computations.

APPENDIX C

SAMPLE OUTPUT FROM PROGRAM RLAC

VERTICAL ACCELERATIONS ON A CATAMARAN IN BEAM SEAS - ASR ASYMMETRICAL HULL-FORM - MODEL 5061

STATION	BEAM (FT)	DRAFT (FT)	AREA (FT2)	AREA COEFF.
0.	0.	0.	0.	0.
0.500	2.000	8.930	9.984	0.559
1.000	3.600	12.450	24.606	0.549
1.500	5.300	14.260	42.173	0.558
2.000	6.960	15.020	62.410	0.597
3.000	10.390	16.500	119.147	0.695
4.000	13.660	18.000	175.804	0.715
5.000	16.930	18.000	239.526	0.786
6.000	19.750	18.000	298.620	0.840
7.000	21.860	18.000	349.804	0.889
8.000	23.070	18.000	387.022	0.932
9.000	23.750	18.000	412.965	0.966
10.000	24.000	18.000	423.792	0.981
11.000	24.000	18.000	4[illegible]6.176	0.968
12.000	24.000	18.000	401.760	0.930
13.000	24.000	18.000	367.200	0.850
14.000	24.000	18.000	315.792	0.731
15.000	23.440	18.000	255.684	0.606
16.000	21.690	18.000	188.963	0.484
17.000	18.840	15.650	128.553	0.436
18.000	14.700	10.780	74.321	0.469
18.500	12.080	4.360	31.075	0.590
19.000	9.040	2.920	15.785	0.598
19.500	5.350	1.470	4.451	0.566
20.000	0.990	0.	0.	0.

```
VERTICAL ACCELERATIONS ON A CATAMARAN IN BEAM SEAS  -  ASR ASYMMETRICAL HULL-FORM  -  MODEL 5061

RHO =  WATER DENSITY  =  1.9905 LB-SEC2/FT4             G  =  ACCELERATION OF GRAVITY  =  32.174 FT/SEC2
L   =  LENGTH BETWEEN PERPENDICULARS OF EACH HULL             =  210.000 FT
B   =  FULL BEAM OF EACH HULL AT MIDSHIPS (STA.10)            =   24.000 FT
H   =  DRAFT (WL TO KEEL) AT MISDHIPS                         =   18.000 FT
VOL =  VOLUME OF WATER DISPLACED BY BOTH HULLS                =   97756. FT3
M   =  TOTAL MASS OF CATAMARAN  =  RHO * VOL                  =  194583. LB-SEC2/FT
D   =  DISPLACEMENT (GROSS WEIGHT) OF CATAMARAN = M * G       =  6260518. LB  =   2794.9 TONS
AW  =  WATERPLANE AREA OF EACH HULL                           =    3668. FT2
IW  =  MOMENT OF INERTIA OF AW W/RESPECT TO LONG.AXIS OF HULL =  136191. FT4
CB  =  BLOCK COEFFICIENT OF EACH HULL  =  VOL/2/(L*B*H)       =    0.539
CW  =  WATERPLANE COEFFICIENT OF EACH HULL  =  AW/(L*B)       =    0.728
LCB =  LONGITUDINAL CENTER OF BUOYANCY (DISTANCE AFT OF FT)   =     106. FT  =  0.504 L
LCF =  LONGITUDINAL CENTER OF FLOTATION (DISTANCE AFT OF FP)  =     114. FT  =  0.541 L
DK  =  VERTICAL DISTANCE FROM KEEL TO DECK AT MIDSHIPS
BK  =  VERTICAL DISTANCE FROM KEEL TO CENTER OF BUOYANCY (C.B.)
GK  =  VERTICAL DISTANCE FROM KEEL TO CENTER OF GRAVITY (C.G.)
BG  =  VERTICAL DISTANCE FROM C.B. TO C.G.  =  GK - BK
MG  =  METACENTRIC HEIGHT  =  BM + BK - GK
L1  =  HORIZONTAL DISTANCE FROM CL OF CATAMARAN TO CL OF ONE HULL
L2  =  HORIZONTAL DISTANCE FROM CL OF CATAMARAN TO OUTER EDGE OF DECK
SEP =  HULL SEPARATION  = (2 * L1) - B
KG  =  TRANSVERSE GYRADIUS
H13 = SIGNIFICANT WAVE HEIGHT
WL  =  WAVE LENGTH          WH = WAVE AMPLITUDE          WS = WAVE SLOPE = 2 * 3.14 * WH / WL = 3.14/80
W   =  WAVE FREQUENCY  =  FREQUENCY OF ENCOUNTER (BEAM SEAS ONLY)
PHI =  AMPLITUDE OF ROLL ANGLE
S(W) = SEA SPECTRUM (PIERSON-MOSKOWITZ)
RADR*S = (PHI/WH)SQ * S(W)                RADA*S = (PHI*W*W/WH)SQ * S(W)
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VERTICAL ACCELERATIONS ON A CATAMARAN IN BEAM SEAS - ASR ASYMMETRICAL HULL-FORM - MODEL 5061

L(FT)	L/B	B/H	SEP/B	L2(FT)	DK(FT)	GK(FT)	BG(FT)	GM(FT)	RG/L1	D(TONS)
210.000	8.750	1.333	1.405	125.000	117.000	18.700	8.700	50.582	1.046	2794.9

				H13 = 4.0 FT.			H13 = 10.0 FT.			H13 = 20.0 FT.			H13 = 30.0 FT.		
W(L,G)	WL/L	PHI/WS	W(1/SEC)	S(W)	RAOR*S	RADA*S	S(W)	RAOR*S	RADA*S	S(W)	RAOR*S	RADA*S	S(W)	RAOR*S	RADA*S
0.20	157.08	1.12	0.078	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.40	39.27	1.14	0.157	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.000	0.0000	0.0000
0.60	17.45	1.16	0.235	0.	0.	0.	0.	0.	0.	0.000	0.0000	0.0000	0.056	0.0000	0.0000
0.80	9.82	1.19	0.313	0.	0.	0.	0.000	0.0000	0.0000	0.452	0.0000	0.0000	57.608	0.0008	0.0000
1.00	6.28	1.22	0.391	0.000	0.	0.	0.001	0.0000	0.0000	25.585	0.0009	0.0000	186.368	0.0063	0.0001
1.20	4.36	1.25	0.470	0.000	0.0000	0.0000	0.372	0.0000	0.0000	65.430	0.0048	0.0002	170.476	0.0125	0.0006
1.40	3.21	1.28	0.548	0.000	0.0000	0.0000	4.105	0.0006	0.0001	66.921	0.0096	0.0009	112.215	0.0161	0.0014
1.60	2.45	1.32	0.626	0.000	0.0000	0.0000	9.823	0.0025	0.0004	50.445	0.0130	0.0020	66.293	0.0177	0.0027
1.80	1.94	1.36	0.705	0.010	0.0000	0.0000	12.372	0.0055	0.0013	34.359	0.0152	0.0037	41.514	0.0184	0.0045
2.00	1.57	1.42	0.783	0.107	0.0001	0.0000	11.670	0.0085	0.0032	22.809	0.0167	0.0063	25.823	0.0189	0.0071
2.20	1.30	1.50	0.861	0.390	0.0005	0.0003	9.619	0.0115	0.0063	15.202	0.0181	0.0100	16.547	0.0197	0.0108
2.40	1.09	1.61	0.939	0.775	0.0015	0.0012	7.449	0.0145	0.0113	10.291	0.0200	0.0156	10.925	0.0212	0.0165
2.60	0.93	1.77	1.018	1.087	0.0035	0.0038	5.617	0.0182	0.0195	7.103	0.0230	0.0247	7.419	0.0240	0.0258
2.80	0.80	1.97	1.096	1.239	0.0067	0.0097	4.202	0.0228	0.0329	5.003	0.0272	0.0392	5.167	0.0281	0.0405
3.00	0.70	2.06	1.174	1.246	0.0097	0.0184	3.148	0.0245	0.0466	3.593	0.0280	0.0532	3.683	0.0287	0.0545
3.20	0.61	1.65	1.253	1.160	0.0075	0.0184	2.373	0.0153	0.0376	2.629	0.0169	0.0417	2.679	0.0173	0.0425
3.40	0.54	1.02	1.331	1.029	0.0032	0.0101	1.805	0.0057	0.0178	1.956	0.0061	0.0193	1.985	0.0062	0.0196
3.60	0.48	0.59	1.409	0.887	0.0012	0.0046	1.386	0.0018	0.0072	1.477	0.0020	0.0077	1.495	0.0020	0.0078
3.80	0.44	0.34	1.487	0.750	0.0004	0.0020	1.075	0.0005	0.0029	1.132	0.0006	0.0031	1.143	0.0006	0.0031
4.00	0.39	0.21	1.566	0.629	0.0002	0.0009	0.843	0.0002	0.0012	0.879	0.0002	0.0013	0.886	0.0002	0.0013
4.20	0.36	0.13	1.644	0.524	0.0001	0.0005	0.667	0.0001	0.0006	0.690	0.0001	0.0006	0.695	0.0001	0.0006
4.40	0.32	0.09	1.722	0.436	0.0000	0.0003	0.533	0.0000	0.0003	0.548	0.0000	0.0004	0.551	0.0000	0.0004
4.60	0.30	0.08	1.801	0.363	0.0000	0.0002	0.429	0.0000	0.0003	0.440	0.0000	0.0003	0.442	0.0000	0.0003
4.80	0.27	0.07	1.879	0.303	0.0000	0.0002	0.349	0.0000	0.0002	0.356	0.0000	0.0002	0.357	0.0000	0.0002
5.00	0.25	0.06	1.957	0.253	0.0000	0.0002	0.285	0.0000	0.0002	0.290	0.0000	0.0002	0.291	0.0000	0.0002
5.20	0.23	0.04	2.035	0.212	0.0000	0.0001	0.235	0.0000	0.0001	0.239	0.0000	0.0001	0.240	0.0000	0.0001
5.40	0.22	0.03	2.114	0.179	0.0000	0.0001	0.195	0.0000	0.0001	0.198	0.0000	0.0001	0.198	0.0000	0.0001
5.60	0.20	0.02	2.192	0.151	0.0000	0.0000	0.163	0.0000	0.0000	0.165	0.0000	0.0000	0.165	0.0000	0.0000
5.80	0.19	0.01	2.270	0.128	0.0000	0.0000	0.137	0.0000	0.0000	0.139	0.0000	0.0000	0.139	0.0000	0.0000
6.00	0.17	0.01	2.349	0.110	0.0000	0.0000	0.116	0.0000	0.0000	0.117	0.0000	0.0000	0.117	0.0000	0.0000
6.20	0.16	0.02	2.427	0.094	0.0000	0.0000	0.099	0.0000	0.0000	0.099	0.0000	0.0000	0.100	0.0000	0.0000
6.40	0.15	0.02	2.505	0.081	0.0000	0.0001	0.084	0.0000	0.0001	0.085	0.0000	0.0001	0.085	0.0000	0.0001
6.60	0.14	0.02	2.583	0.070	0.0000	0.0001	0.072	0.0000	0.0001	0.073	0.0000	0.0001	0.073	0.0000	0.0001
6.80	0.14	0.02	2.662	0.060	0.0000	0.0001	0.062	0.0000	0.0001	0.063	0.0000	0.0001	0.063	0.0000	0.0001
7.00	0.13	0.02	2.740	0.052	0.0000	0.0001	0.054	0.0000	0.0001	0.054	0.0000	0.0001	0.054	0.0000	0.0001
7.20	0.12	0.01	2.818	0.046	0.0000	0.0000	0.047	0.0000	0.0000	0.047	0.0000	0.0000	0.047	0.0000	0.0000
7.40	0.11	0.01	2.897	0.040	0.0000	0.0000	0.041	0.0000	0.0000	0.041	0.0000	0.0000	0.041	0.0000	0.0000
7.60	0.11	0.00	2.975	0.035	0.0000	0.0000	0.036	0.0000	0.0000	0.036	0.0000	0.0000	0.036	0.0000	0.0000
7.80	0.10	0.01	3.053	0.031	0.0000	0.0000	0.031	0.0000	0.0000	0.032	0.0000	0.0000	0.032	0.0000	0.0000
8.00	0.10	0.01	3.131	0.027	0.0000	0.0000	0.028	0.0000	0.0000	0.028	0.0000	0.0000	0.028	0.0000	0.0000
8.20	0.09	0.01	3.210	0.024	0.0000	0.0000	0.025	0.0000	0.0000	0.025	0.0000	0.0000	0.025	0.0000	0.0000
8.40	0.09	0.01	3.288	0.021	0.0000	0.0000	0.022	0.0000	0.0000	0.022	0.0000	0.0000	0.022	0.0000	0.0000
8.60	0.08	0.01	3.366	0.019	0.0000	0.0000	0.019	0.0000	0.0000	0.019	0.0000	0.0000	0.019	0.0000	0.0000
8.80	0.08	0.00	3.444	0.017	0.0000	0.0000	0.017	0.0000	0.0000	0.017	0.0000	0.0000	0.017	0.0000	0.0000
9.00	0.08	0.00	3.523	0.015	0.0000	0.0000	0.015	0.0000	0.0000	0.015	0.0000	0.0000	0.015	0.0000	0.0000
9.20	0.07	0.01	3.601	0.014	0.0000	0.0000	0.014	0.0000	0.0000	0.014	0.0000	0.0000	0.014	0.0000	0.0000
9.40	0.07	0.01	3.679	0.012	0.0000	0.0000	0.012	0.0000	0.0000	0.012	0.0000	0.0000	0.012	0.0000	0.0000
9.60	0.07	0.01	3.758	0.011	0.0000	0.0000	0.011	0.0000	0.0000	0.011	0.0000	0.0000	0.011	0.0000	0.0000
9.80	0.07	0.01	3.836	0.010	0.0000	0.0000	0.010	0.0000	0.0000	0.010	0.0000	0.0000	0.010	0.0000	0.0000
10.00	0.06	0.00	3.914	0.009	0.0000	0.0000	0.009	0.0000	0.0000	0.009	0.0000	0.0000	0.009	0.0000	0.0000

VERTICAL ACCELERATIONS ON A CATAMARAN IN BEAM SEAS - ASR ASYMMETRICAL HULL-FORM - MODEL 5861

L(FT)	L/B	B/H	SEP/B	L2(FT)	DK(FT)	GK(FT)	BG(FT)	GM(FT)	RG/L1	D(TONS)
210.000	8.750	1.333	1.405	125.000	117.000	18.700	8.700	56.582	1.046	2794.9

SIGNIFICANT WAVE HEIGHT (FT)	4.00	10.00	20.00	30.00	
SIGNIFICANT ROLL ANGLE (DEGREES)	5.96	11.67	14.43	15.67	SINGLE AMPLITUDE
SIGNIFICANT ROLL ACCELERATION (DEG/SEC2)	8.58	14.01	15.42	15.75	
SIGN.VERTICAL ACC. / G (125.0 FT FROM CL)	0.582	0.950	1.046	1.068	
SIGN. HORIZ. ACC. / G ' 98.3 FT ABOVE VCG)	0.458	0.747	0.822	0.840	

APPENDIX D

FORTRAN LISTING OF PROGRAM RLAC

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      COMMON/BL1/TITLE(12)
      COMMON/BL2/NFR,OMLG(50),ADMH(50),DAMH(50)
      DIMENSION NM(30),B(30),H(30),CA(30),AR(30),ST(30),X(30),AM(30),
     1 B3(30),SHB(30),DS(30),Y(20,30),Z(20,30),OM(50),A33(50),B33(50),
     2 H13(4),FROLL(50,4),FACC(50,4),RDEG(4),AVG(4),AHG(4),SW(4),ADEG(4)
      RAD=57.2958
      RHO=1.9905
      G=32.174
      RHG=RHO*G
      PI=3.1415926
      PI2=2.*PI
      PI2G=PI2*G
      G81=.0081*G*G
    1 READ (5,500) (TITLE(J),J=1,12)
      READ (5,502) BPL,OMIN,OMAX,DOM,CST,NOS,IAMD
      READ (5,504) (ST(K),B(K),H(K),CA(K),NM(K),K=1,NOS)
      NUX=NM(1)
      DO 8 K=2,NOS
      IF (ST(K).NE.10.) GO TO 5
      MS=K
    5 IF (NUX.GE.NM(K)) GO TO 8
      NUX=NM(K)
    8 CONTINUE
      IF (MS.NE.0) GO TO 10
      WRITE(6,606)
      GO TO 1
   10 SS=BPL/20.
      DO 15 K=1,NOS
      IF (NM(K).NE.0) GO TO 11
      B(K)=B(K)*CST
      H(K)=H(K)*CST
      AR(K)=CA(K)*B(K)*H(K)
      GO TO 13
   11 NZ=NM(K)
      READ (5,506) (Y(J,K),J=1,NZ)
      READ (5,506) (Z(J,K),J=1,NZ)
      H(K)=Z(NZ,K)-Z(1,K)
       B(K)=2.*Y(NZ,K)
      AR(K)=2.*SIMPUN(Z(1,K),Y(1,K),NZ)
      B(K)=B(K)*CST
      H(K)=H(K)*CST
      AR(K)=AR(K)*CST**2
      CA(K)=AR(K)/(B(K)*H(K))
   13 X(K)=SS*ST(K)
      AM(K)=X(K)*AR(K)
   15 B3(K)=(0.5*B(K))**3
      IF (IAMD.GT.0) GO TO 31
   16 DO 30 K=1,NOS
      IF (B(K).LE.0.0.OR.H(K).LE.0.) GO TO 30
      AC=CA(K)
      RAT=0.5*B(K)/H(K)
      TAR=1./RAT
      IF (RAT.LE.1.) GO TO 23
      BL=0.29456*(2.-TAR)
      GO TO 24
```

```
23 BL=0.29456*(2.-RAT)
24 UL=0.098125*(RAT+TAR+10.)
   IF (CA(K).GT.BL) GO TO 25
   CA(K)=BL+0.0001
   GO TO 26
25 IF(CA(K).LT.UL) GO TO 30
   CA(K)=UL-0.0001
26 WRITE(6,608) ST(K),AC,CA(K)
   AR(K)=CA(K)*B(K)*H(K)
   AM(K)=X(K)*AR(K)
30 CONTINUE
31 CONTINUE
   WRITE(6,600) (TITLE(J),J=1,12)
   WRITE(6,602)
   DO 35 K=1,NOS
35 WRITE(6,604) ST(K),B(K),H(K),AR(K),CA(K)
   VOL=SIMPUN(X,AR,NOS)
   BM=B(MS)
   HM=H(MS)
   CB=VOL/(BPL*BM*HM)
   AW=SIMPUN(X,B,NOS)
   CW=AW/(BPL*BM)
   BOY=SIMPUN(X,AM,NOS)/VOL
   CBL=BOY/BPL
   DO 38 K=1,NOS
38 SHB(K)=(X(K)-BOY)*B(K)
   FLC=BOY+SIMPUN(X,SHB,NOS)/AW
   CFL=FLC/BPL
   VOL=VOL*2.
   DLBS=RHG*VOL
   OIP=SIMPUN(X,B3,NOS)*0.6666667
   TM=VOL*RHO
   BL=BPL/BM
   BT=BM/HM
   DTONS=DLBS/22' ).
   WRITE(6,600) (TITLE(J),J=1,12)
   WRITE(6,610) BPL,BM,HM,VOL,TM
   WRITE(6,612) DLBS,DTONS,AW,OIP,CB,CW
   WRITE(6,614) BOY,CBL,FLC,CFL
   WRITE(6,615)
   WRITE(6,616)
   WRITE(6,618)
   VOLND=VOL/(2.*BPL**3)
   DO 40 K=1,NOS
   B(K)=B(K)/BPL
40 H(K)=H(K)/BPL
   NFR=(OMAX-OMIN)/DOM+1.2
   OMLG(1)=OMIN
   B33(1)=0.
   A33(1)=0.
   DO 45 N=2,NFR
   OMLG(N)=OMLG(N-1)+DOM
   A33(N)=0.
   B33(N)=0.
45 CONTINUE
   IF (NAMD.GT.0) GO TO 56
```

```
      CALL NILS(NOS,MS,ST,DS,JFK)
      IF (JFK.EQ.0) GO TO 1
      DO 50 K=1,NOS
      CALL ADMAB(B(K),H(K),CA(K))
      DO 50 N=1,NFR
      A33(N)=A33(N)+DS(K)*ADMH(N)
   50 B33(N)=B33(N)+DS(K)*DAMH(N)
      DO 55 N=1,NFR
      A33(N)=A33(N)/(OMLG(N)**2*VOLND)
   55 B33(N)=B33(N)/(OMLG(N)*VOLND)
      GO TO 58
   56 READ (5,506) (A33(N),N=1,NFR)
      READ (5,506) (B33(N),N=1,NFR)
   58 H2L=0.02
      WS=H2L*PI
      READ (5,510) NSWH
      READ (5,508) (H13(M),M=1,NSWH)
      READ (5,510) NC
      DO 100 NCD=1,NC
      READ (5,508) BP,DK,GK,BK,YLP,YL,RG
      IF (BP.EQ.BPL) GO TO 60
      RL=BP/BPL
      BPL=BP
      RL2=RL*RL
      RL3=RL2*RL
      RL4=RL3*RL
      VOL=VOL*RL3
      AW=AW*RL2
      OIP=OIP*RL4
      DLBS=DLBS*RL3
      DTONS=DTONS*RL3
      TM=TM*RL3
      BM=BM*RL
      HM=HM*RL
      DK=DK*RL
      BK=BK*RL
   60 VOL1=VOL/2.
      TMGL=TM*SQRT(G/BPL)
      YLB=YL/BM
      YL2=YL**2
      SRLG=SQRT(BPL/G)
      GD=DK-GK
      OI=2.*(OIP+YL2*AW)
      RG2=RG*RG
      RGL=RG/YL
      SEP=(2.*YL-BM)/BM
      TMI=RG2*TM
      BG=GK-BK
      BMM=OI/VOL
      GM=BK+BMM-GK
      CRM=(OI/VOL-BG)*DLBS
      OFV=OIP-BG*VOL1
      WRITE(6,600) (TITLE(J),J=1,12)
      WRITE(6,620) BPL,BL,BT,SEP,YLP,DK,GK,BG,GM,RGL,DTONS
      WRITE(6,623) (H13(M),M=1,4)
      DO 80 N=1,NFR
```

```
      OM(N)=OMLG(N)/SRLG
      OM2=OM(N)**2
      OM4=OM2*OM2
      OM5=OM4*OM(N)
      WL=PI2G/OM2
      WLL=WL/BPL
      WH2=H2L*WL
      WH=0.5*WH2
      ANG=PI2*YL/WL
      PWL=PI2/WL
      FBAR=WH2*RHG*SQRT((YL*AW*EXP(-PWL*VOL1/AW)*SIN(ANG))**2 +
     1 (PWL*OFV*COS(ANG))**2)
      CM=TMI+YL2*A33(N)*TM
      CN=YL2*B33(N)*TMGL
      PHIB=FBAR/SQRT((CRM-CM*OM2)**2+CN**2*OM2)
      PHIB=ABS(PHIB)
      PHI=PHIB/WS
      RAOR=(PHIB/WH)**2
      RACA=RAOR*CM4
      DO 70 M=1,NSWH
      SW(M)=G81/OM5*EXP(-33.56/(H13(M)**2*OM4))
      FROLL(N,M)=RAOR*SW(M)
   70 FACC (N,M)=RAOA*SW(M)
   80 WRITE(6,624) OMLG(N),WLL,PHI ,OM(N),(SW(M),FROLL(N,M),FACC(N,M),
     1 M=1,4)
      DO 85 M=1,NSWH
      E2=SIMPUN(CM,FROLL(1,M),NFR)
      RDEG(M)=SQRT(E2)*2.0*RAD
      E2=SIMPUN(CM, FACC(1,M),NFR)
      SRE=SQRT(E2)*2.0
      ADEG(M)=SRE*RAD
      AVG(M)=YLP*SRE/G
      AHG(M)=GD *SRE/G
   85 CONTINUE
      WRITE(6,600) (TITLE(J),J=1,12)
      WRITE(6,620) BPL,BL,BT,SEP,YLP,DK,GK,BG,GM,RGL,DTONS
      WRITE(6,630) (H13(M),M=1,4),(RDEG(M),M=1,4),(ADEG(M),M=1,4),YLP,
     1 (AVG(M),M=1,4),GD,(AHG(M),M=1,4)
  100 CONTINUE
      GO TO 1
  500 FORMAT (12A6)
  502 FORMAT (5F9.3,2I9)
  504 FORMAT (4F9.4,I9)
  506 FORMAT (8F9.4)
  508 FORMAT (8F9.3)
  510 FORMAT (I2)
  600 FORMAT (59H1     VERTICAL ACCELERATIONS ON A CATAMARAN IN BEAM SEA
     1S  - ,12A6)
  602 FORMAT (1H0/73H       STATION      BEAM (FT)     DRAFT (FT)    ARE
     1A (FT2)    AREA COEFF.  )
  604 FORMAT (5F14.3)
  606 FORMAT (1H0,22HSTATION 10.0 NOT GIVEN  )
  608 FORMAT (1H0,10HSTATION = ,F9.4,6X,30HAREA COEFFICIENT CHANGED FROM
     1   ,F10.4,2X,2HTO,2X,F10.4)
  610 FORMAT (49H0      RHO =  WATER DENSITY  =  1.9905 LB-SEC2/FT4, 15X,
     1 48HG  =  ACCELERATION OF GRAVITY  =  32.174 FT/SEC2 // 6X,
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   2 49HL    =  LENGTH BETWEEN PERPENDICUL..RS OF EACH HULL,15X,1H=,
   3 F10.3,3H FT // 6X, 50HB    =  FULL BEAM OF EACH HULL AT MIDSHIPS (
   4STA.10),14X,1H=,F10.3,3H FT // 6X,37HH    =  DRAFT (WL TO KEEL) AT
   5MISDHIPS, 27X,1H=,F10.3,3H FT // 6X,46HVOL =  VOLUME OF WATER DISP
   6LACED BY BOTH HULLS,18X,1H=,F10.0, 4H FT3 // 6X, 44HM    =  TOTAL M
   7ASS OF CATAMARAN  =  RHO * VOL,20X,1H=,F10.0,11H LB-SEC2/FT  )
612 FORMAT (61H0     D    =  DISPLACEMENT (GROSS WEIGHT) OF CATAMARAN =
   1 M * G, 9X,1H=,F10.0, 6H LB  =, F10.1,5H TONS// 6X,35HAW  =  WATER
   2PLANE AREA OF EACH HULL,29X,1H=,F10.0,4H FT2 // 6X, 65HIW  =  MOME
   3NT OF INERTIA OF AW W/RESPECT TO LONG.AXIS OF HULL   =,F10.0,
   4 4H FT4 // 6X, 55HCB  =  BLOCK COEFFICIENT OF EACH HULL  =  VOL/2/
   5(L*B*H),9X,1H=,F10.3// 6X, 55HCW  =  WATERPLANE COEFFICIENT OF EAC
   6H HULL  =  AW/(L*B),9X,1H=,F10.3)
614 FORMAT (71H0     LCB =  LONGITUDINAL CENTER OF BUOYANCY (DISTANCE
   1AFT OF FT)     =,F10.0,6H FT  =,F7.3,2H L // 71H     LCF =  LONGI
   2TUDINAL CENTER OF FLOTATION (DISTANCE AFT OF FP)    =,F10.0,
   36H FT  =,F7.3,2H L  )
615 FORMAT (60H0     DK  =  VERTICAL DISTANCE FROM KEEL TO DECK AT MID
   1SHIPS // 69H     BK  =  VERTICAL DISTANCE FROM KEEL TO CENTER OF
   2BUCYANCY (C.B.)  )
616 FORMAT(68H0     GK  =  VERTICAL DISTANCE FROM KEEL TO CENTER OF GR
   1AVITY (C.G.) //6X,54HBG  =  VERTICAL DISTANCE FROM C.B. TO C.G.  =
   2  GK - BK // 6X, 50HMG  =  METACENTRIC HEIGHT  =  BM + BK - GK
   3    // 6X, 65HL1  =  HORIZONTAL DISTANCE FROM CL OF CATAMARAN TO C
   4L OF ONE HULL // 6X, 69HL2  =  HORIZONTAL DISTANCE FROM CL OF CATA
   5MARAN TO OUTER EDGE OF DECK // 6X, 38HSEP =  HULL SEPARATION  = (2
   6 * L1) - B // 6X, 26HRG  =  TRANSVERSE GYRADIUS // 6X, 30HH13 = SI
   7GNIFICANT WAVE HEIGHT // 6X, 18HWL  =  WAVE LENGTH,10X,19HWH = WAV
   8E AMPLITUDE,10X,46HWS = WAVE SLOPE = 2 * 3.14 * WH / WL = 3.14/50)
618 FORMAT (71H0     W   =  WAVE FREQUENCY  =  FREQUENCY OF ENCOUNTER
   1(BEAM SEAS ONLY) // 6X,30HPHI =  AMPLITUDE OF ROLL ANGLE // 6X,
   2 39HS(W) = SEA SPECTRUM (PIERSON-MOSKOWITZ. // 6X,
   3 26HRAOR*S = (PHI/WH)SQ * S(W) , 15X,
   4 30HRAOA*S = (PHI*W*W/WH)SQ * S(W)  )
620 FORMAT (128H0   L(FT)       L/B        B/H        SEP/B       L2(FT)
   1        DK(FT)      GK(FT)      BG(FT)      GM(FT)       RG/L1
   2 D(TONS) / 3F10.3,7F12.3,F14.1 )
622 FORMAT (1H0)
623 FORMAT (1H0,30X,4(7X,5HH13 =,F5.1,4H FT,,4X) / 31X,4(2X,23(1H-)) /
   1131H W(L/G)   WL/L    PHI/WS   W(1/SEC)    S(W)    RAOR*S  RAOA*S    S(
   2W)   RAOR*S  RAOA*S     S(W)    RAOR*S  RAOA*S     S(W)    RAOR*S  RAO
   3A*S )
624 FORMAT(F6.2,F7.2,F8.2,F9.3,1X,4(F9.3,2F8.4))
630 FORMAT (1H0,5X,28HSIGNIFICANT WAVE HEIGHT (FT),21X,4F10.2 /
   1 1H0,5X,32HSIGNIFICANT ROLL ANGLE (DEGREES),17X,4F10.2 /
   2 1H0,5X,40HSIGNIFICANT ROLL ACCELERATION (DEG/SEC2),9X,4F10.2/
   3 1H0,5X,26HSIGN.VERTICAL ACC. / G    ( ,F6.1,12H FT FROM CL), 5X
   4 ,4F10.3 / 1H0,5X,26HSIGN. HORIZ.  ACC. / G    ( , F6.1,
   5 17H FT ABOVE VCG)    , 4F10.3)
    END
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REFERENCES

1. Frank, W. and Salvesen, N., "The Frank Close-Fit Ship-Motion Computer Program," NSRDC Report 3289 (Jun 1970).

2. Joosen, W.P.A. et al., "Vertical Motions and Bending Moments in Regular Waves, a Comparison Between Calculation and Experiment," International Shipbuilding Progress (1968).

3. Vassilopoulos, L. and Mandel, P., "A New Appraisal of Strip Theory," Proceedings of the Fifth Symposium on Naval Hydrodynamics, Bergen, Norway (1964).

4. Wahab, R., "The Rolling Motion of a Catamaran at Sea," Netherlands Ship Model Basin Publication 230 (1964).

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Simplified methods are discussed for estimating (1) the pitch and heave of catamarans in head seas based on theory which has proved successful for conventional single hulled ships, and (2) the roll of catamarans in beam seas by representing the small amount of roll as alternate heaving of the two hulls. Both prediction methods neglect interaction effects between the two hulls. Computed values of pitch, heave, and roll are compared with experimental data from model tests of a catamaran in regular waves. Documentation of the computer program for predicting the roll of a catamaran in regular and irregular seas is presented ~~in the~~ appendices.

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